BNL -FNAL - LBNL - SLAC

LARP DOE Review
June 12-14, 2006

2.4.1 Materials – Conductor Support

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Introduction

Strand Stability

Strand R&D

Cable R&D

Summary

Main Goals

Two goals for the Materials R&D Program

- Characterize “baseline” strand for the magnet program
- Support R&D program for development of future LARP material
  - (augmented with significant core program support)

Nb_3Sn Strand

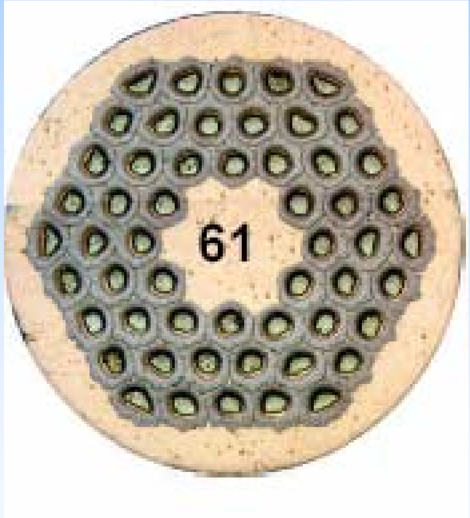
Magnets for LARP are designed to use high J_c (> 2400 A/mm2 at 12T) Nb_3Sn wires.

- Current Strand Options
  - MJR (Modified Jelly Roll) – OST (Oxford Superconducting Technology) has discontinued this wire
  - RRP (Re-Stack Rod Process) – OST production wire (commercial applications, US magnet programs)
  - PIT (Powder-in-Tube)– unreliable delivery, high cost
  - Future Strand Development
    - DOE SBIR(Small Business Innovative Research) program
    - DOE Conductor Development Program (CDP)
    - Core programs (e.g. FNAL procurement of PIT and RRP wires)
    - Conductor Development under NED (Next European Dipole)

"Baseline Strand"- Specs.

- **LARP Magnets will use OST production Wire**

- **R**od **R**e-Stack **P**rocess, RRP 54/61 Design
  - 0.7mm diameter
  - Sub-element (Filament) Diameter ~ 70 μm
  - $J_c > 2400 A/mm^2$ at 12T
  - $I_c > 500$ A at 12T
  - Copper Fraction 47%
  - RRR of stabilizer Cu > 100
  - Stability current $I_s \sim 1000$ A



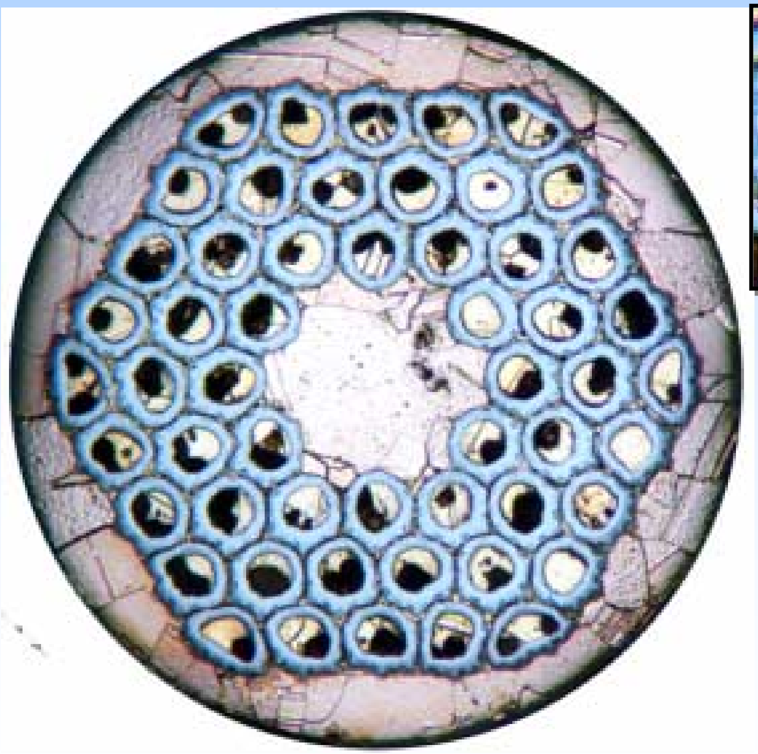
- Magnet Operating Current ~ 500 A (~ 12T)

For the strand $I_s > 2 \times I_{op}$

Key issue for high Jc-Nb_3Sn Strand

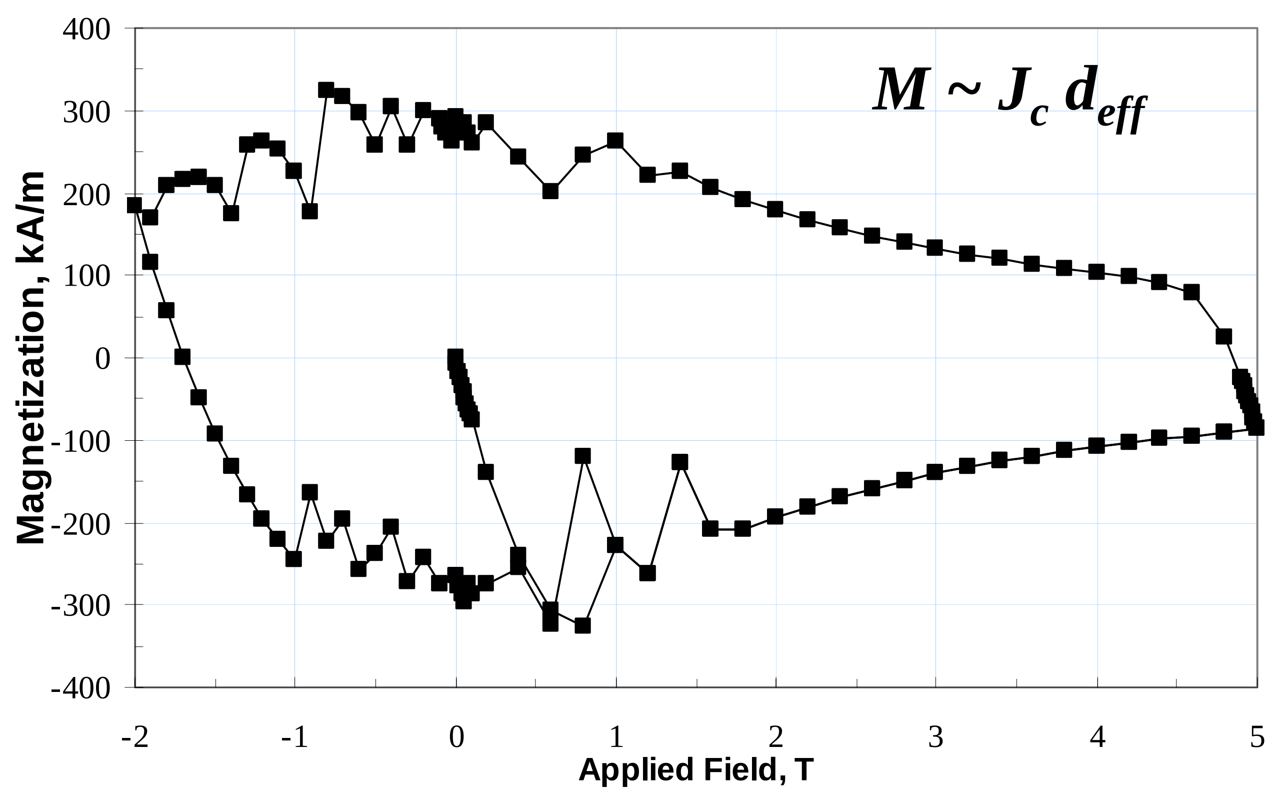
Lack of "Adiabatic" stability in currently available strands (RRP 54/61 design)

After reaction strand is essentially a 54-filament conductor with filament diameter d_{eff} ~ sub-element diameter



Key issue for high Jc-Nb_3Sn Strand

The combination of high *Jc* and large *d* results in the loss of "adiabatic" stability at low fields ⇨Flux-jumps



0.7mm strands

54 Filaments

Deff ~ 70 μm

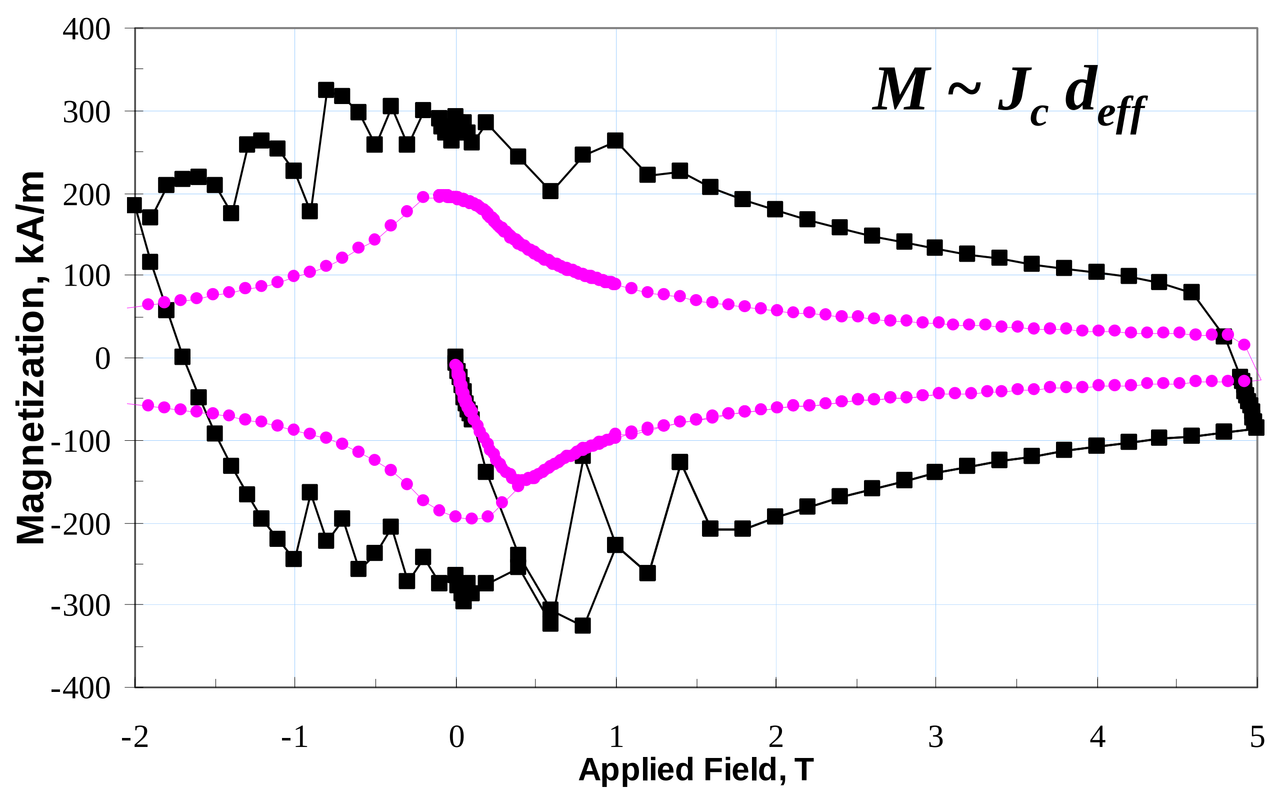
Key issue for high Jc-Nb_3Sn Strand

The combination of high *Jc* and large *d* results in the loss of "adiabatic" stability at low fields ⇨ Flux-jumps

R&D

Restore "adiabatic" stability ➢ Make small Filaments

Reduce ***d to less than 35 μm*** ➢ increase number of filaments



0.7mm strands

54 Filaments

Deff ~ 70 μm

0.8mm strand

NED R&D PIT

288 Filaments

Deff ~ 32 μm

Flux-Jump Instability

Key concern specific to LARP strand and TQ magnet operating current of 500 A

Since wires of 0.7 mm with d_{eff} < 35 μm cannot be made at present, flux-jumps are inevitable in low-field regions of magnets.

Will "flux jump" initiate a quench ?

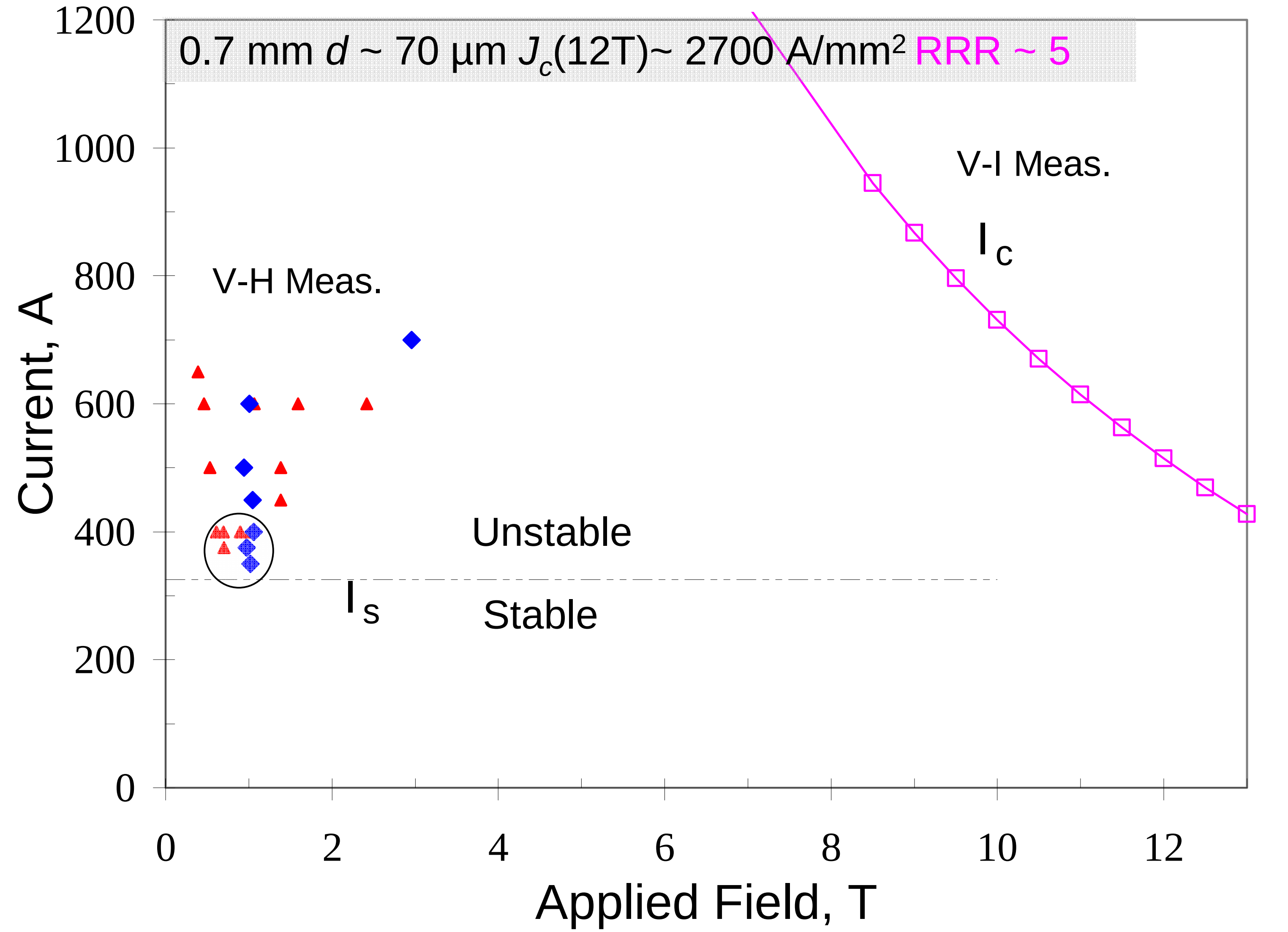
Not if: local copper stabilizer RRR is "high"

Strand Stability

↓

Evaluated by measuring I_s

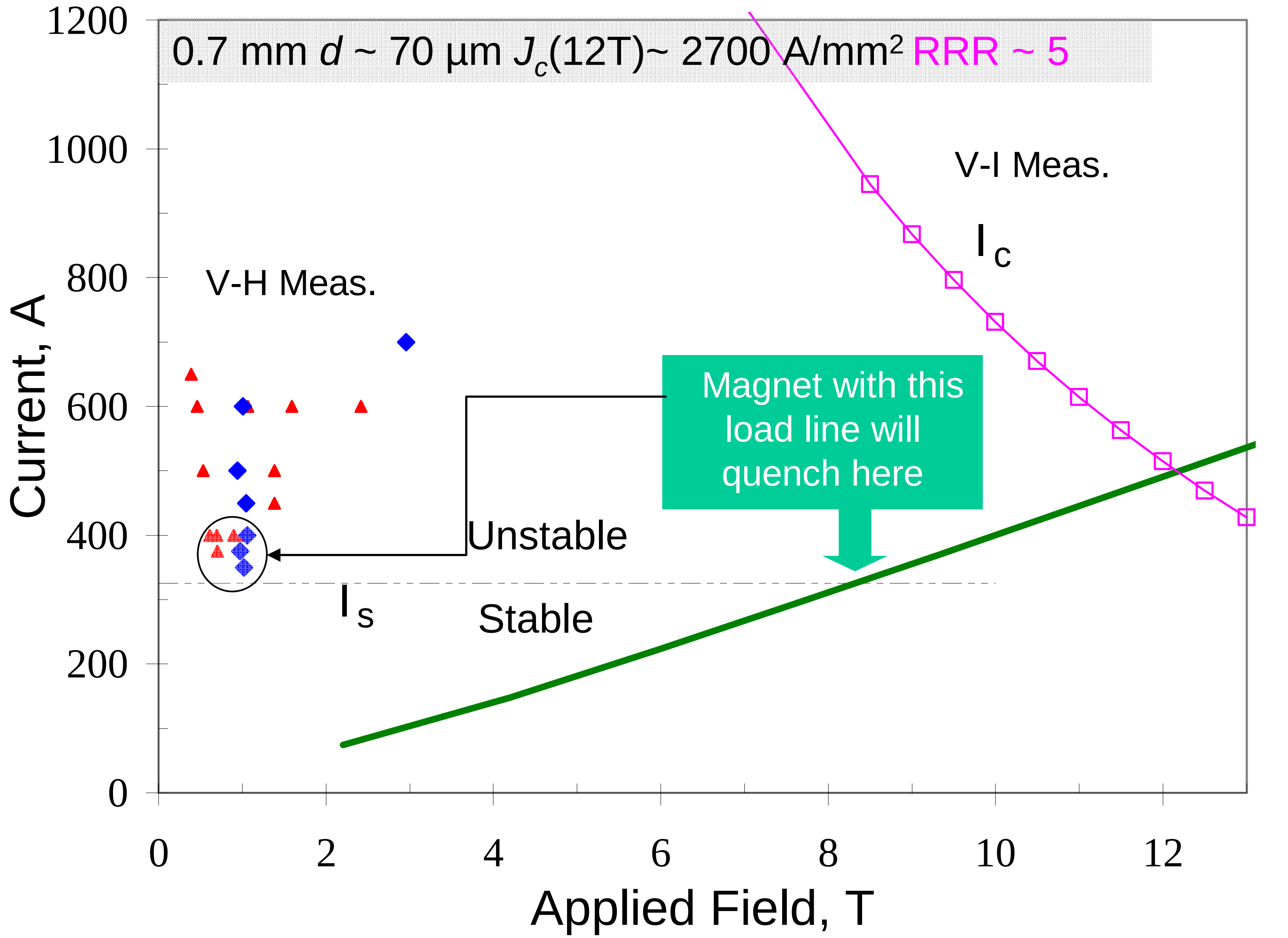
Stability Current Is



Unstable

Stable

Stability Current Is



Unstable

Stable

Why is RRR low ?

- High Jc is achieved by reacting the most Nb area, including the Nb diffusion barrier.

However

- ➢ Reactions: to get high Jc allow tin (Sn) to react through the Nb-barrier and poison the surrounding copper.

Sn Leakage leads to low copper RRR

Instability Management

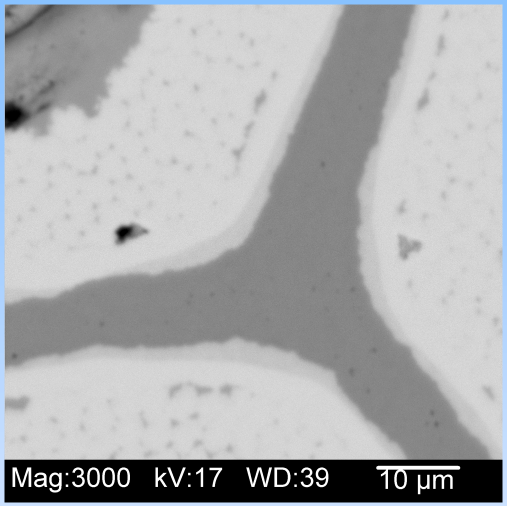
- Tin leakage into copper destroys "*dynamic stability*" by increasing its resistivity ρ which also reduces thermal conductivity k_{TH} *(which affects heat transfer within the strand and to the coolant)*
- Copper RRR reduces from 300 to 7 for as little as 0.1% Sn
- Measurements show that RRR (~ 1/ρ) of the copper stabilizer influences I_s
  - I_s increases with increasing RRR

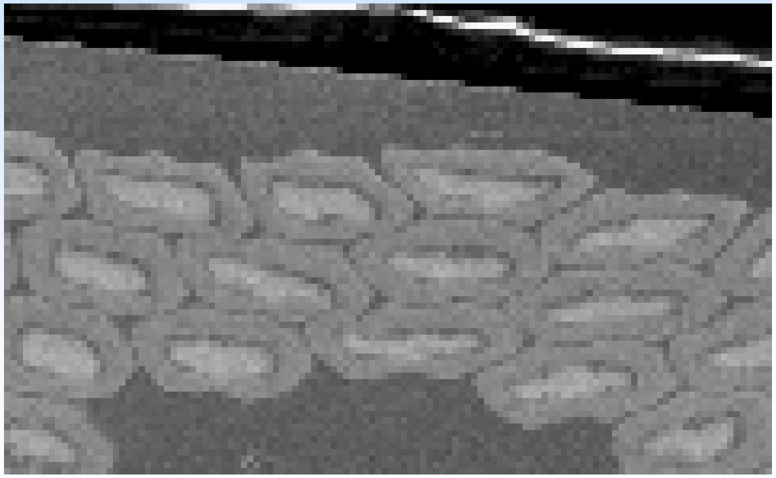
Manage Instability by HT Optimization – Trade some J_c for high RRR in strand

Minimize Sn-Leakage into stabilizer

Even for moderate reactions Sn leakage can still occur due to

- Diffusion barrier thins or tears during the wire fabrication process.
  - ⇨ *Measure Is for round strands*
- Strand deformation (e.g. cabling) distorts sub-elements and diffusion barrier.
  - ⇨ Adjust cabling parameters and procedures to minimize filament distortion
  - ⇨ *Measure Is for extracted strands*
  - ⇨ *Measure Is for cables*





Strand R&D
Main Activities

- –Round Strand Characterization
  - Ic, Is, RRR, M
  - Heat-treatment optimization
- –Extracted Strand test
  - Ic and Is
  - Predict performance of LARP magnets
- –Rolled Strand tests (new for LARP)

Strand Test –Facility Resources

FOR STRAND Ic TESTS

(MAX FIELD 4.2K/1.9K ,POWER SUPPLY MAX CURRENT)

FNAL: 15/17 T, 1800 A; 14/16 T (large bore), 1000 A

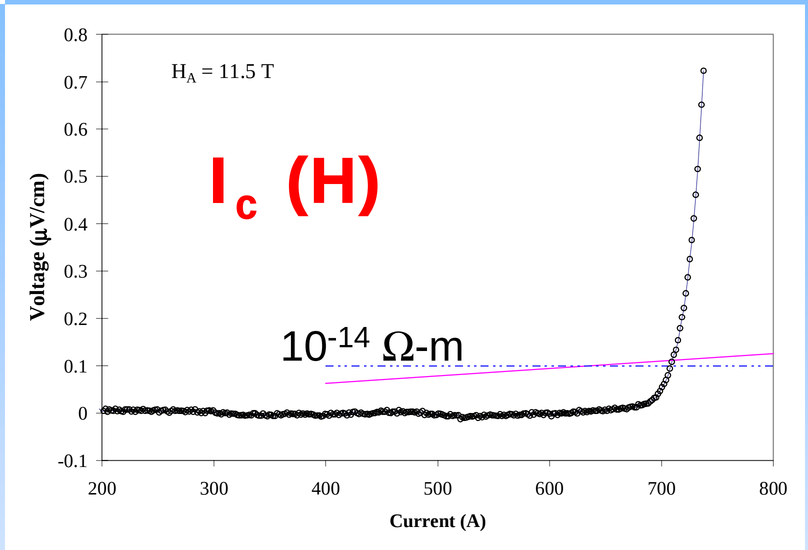
LBNL: 15 T, 2000 A

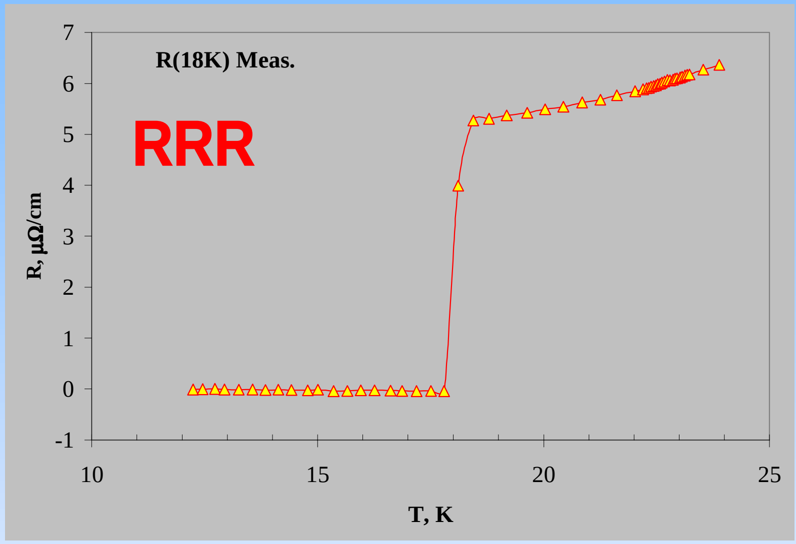
BNL: 11.5/12 T, 1500 A

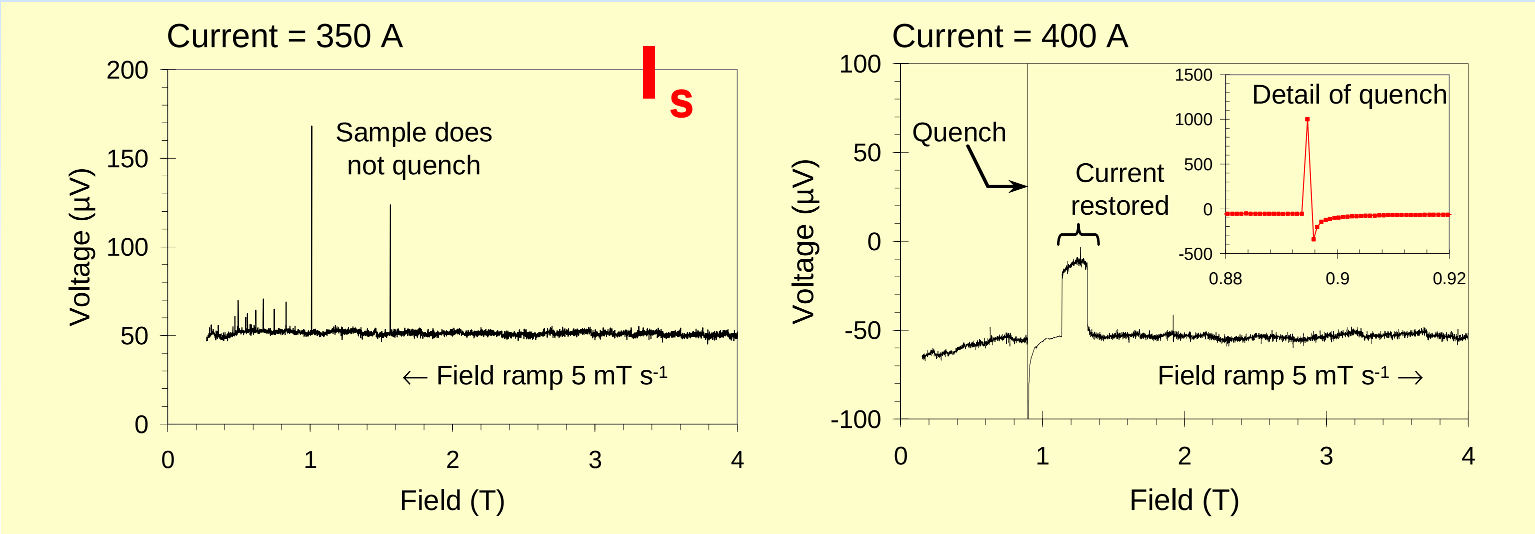
At present all of the strand testing is being done at BNL and FNAL. LBNL test station is being upgraded.

During the first six months of FY06, 120 round and extracted strands were measured.

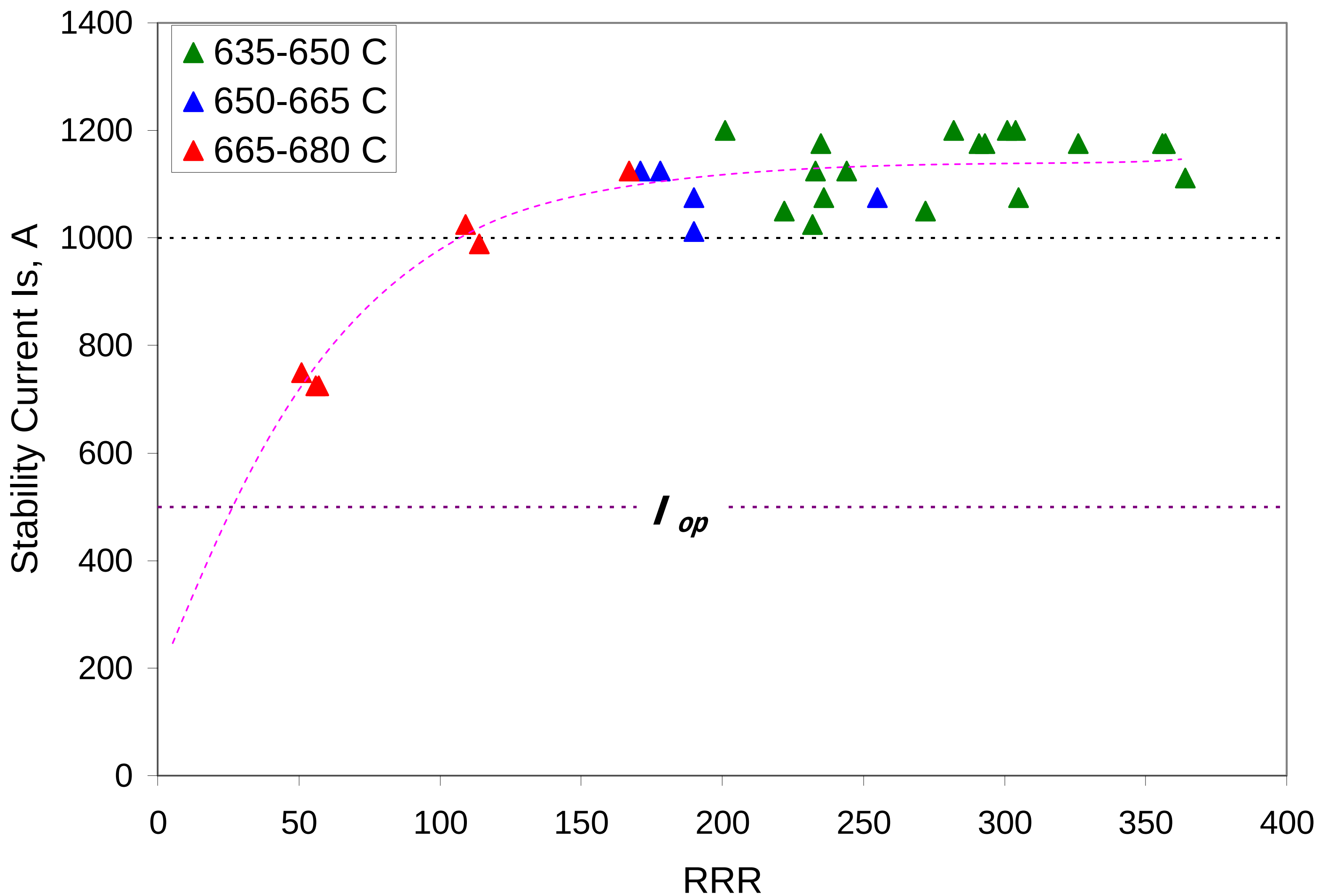
Billet Characterization- Ic ,Is and RRR



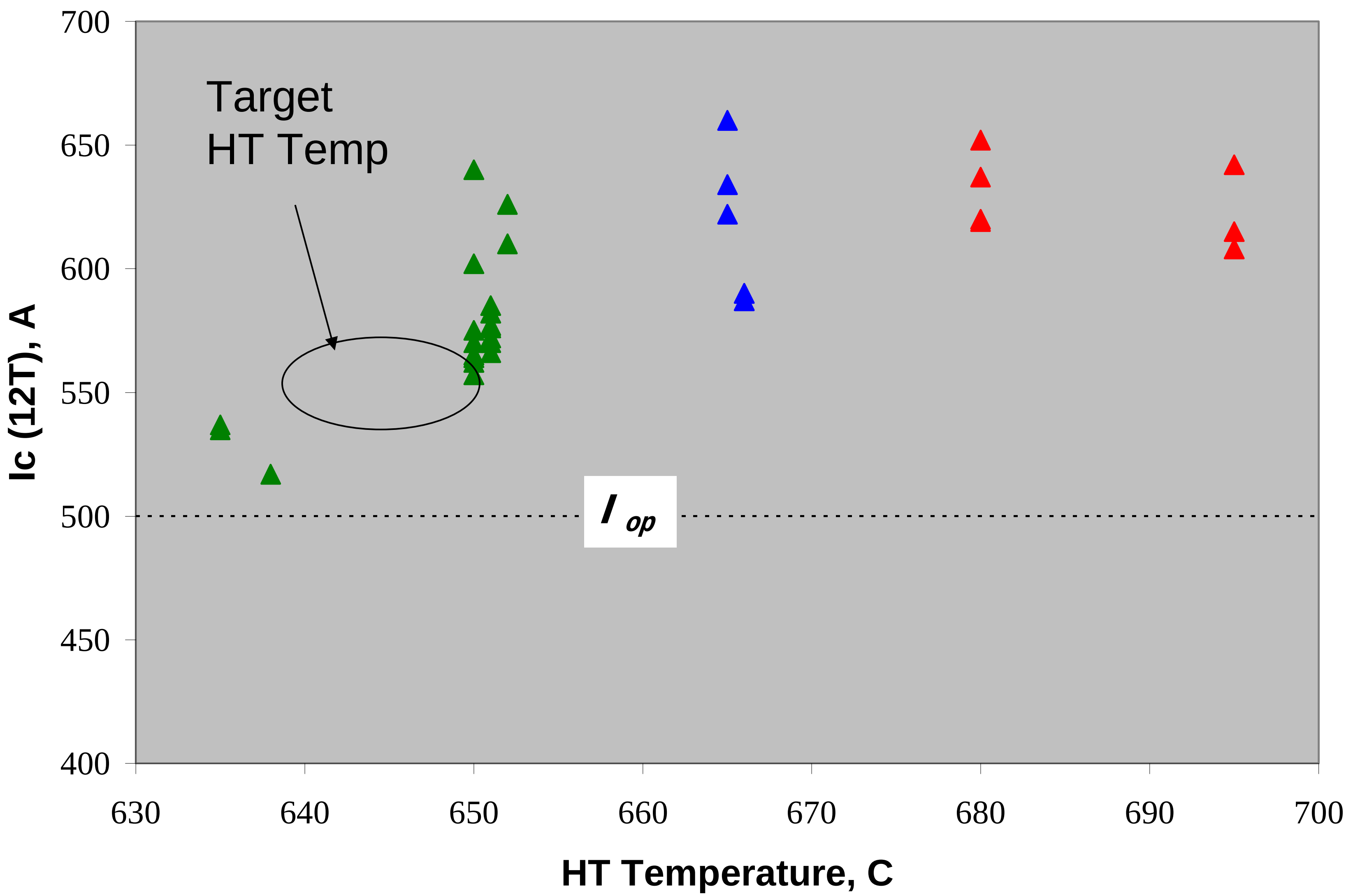




Is vs. RRR for LARP strands– 5 Billets (160kg)



Critical Current of RRP Billets



Reaction Temperatures

Measurements indicate that reaction temperatures less than 650 ^{o}C (for a duration of 48 hrs) are suitable to maintain a high RRR and 12T critical currents that exceed 500 A with ~ 10% margin.

Round Robin BNL-FNAL

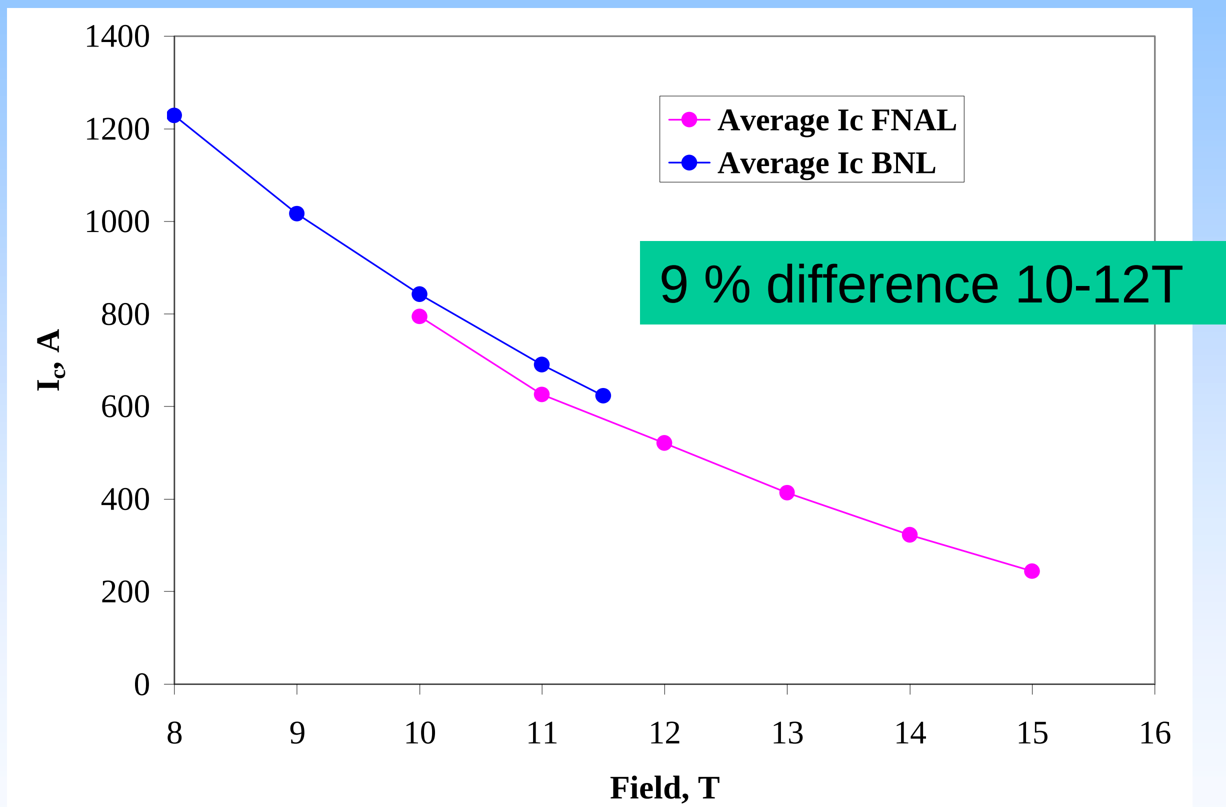
2 samples measured at FNAL and two at BNL. All samples reacted at BNL.

Strand ID I_c, A at	14 T	13 T	12 T [a]	10 T	8 T	Is, A	RRR
FNAL	245±2	317±2	402±1	612±2		980±170	211±11
FNAL w/sty	252±3	320±2	406	616	911	975±110	
BNL			[415]±7	621±8	905±9	1100±140	189±66
BNL w/sty			[421]±1	629±3	909	1100	

- For round strands, I_c at 12 T is within 3%, at 8T it is < 1%

Extracted Strands –Round Robin

2 samples measured at FNAL and three at BNL. All samples reacted at BNL during SRS01 coil reactions.

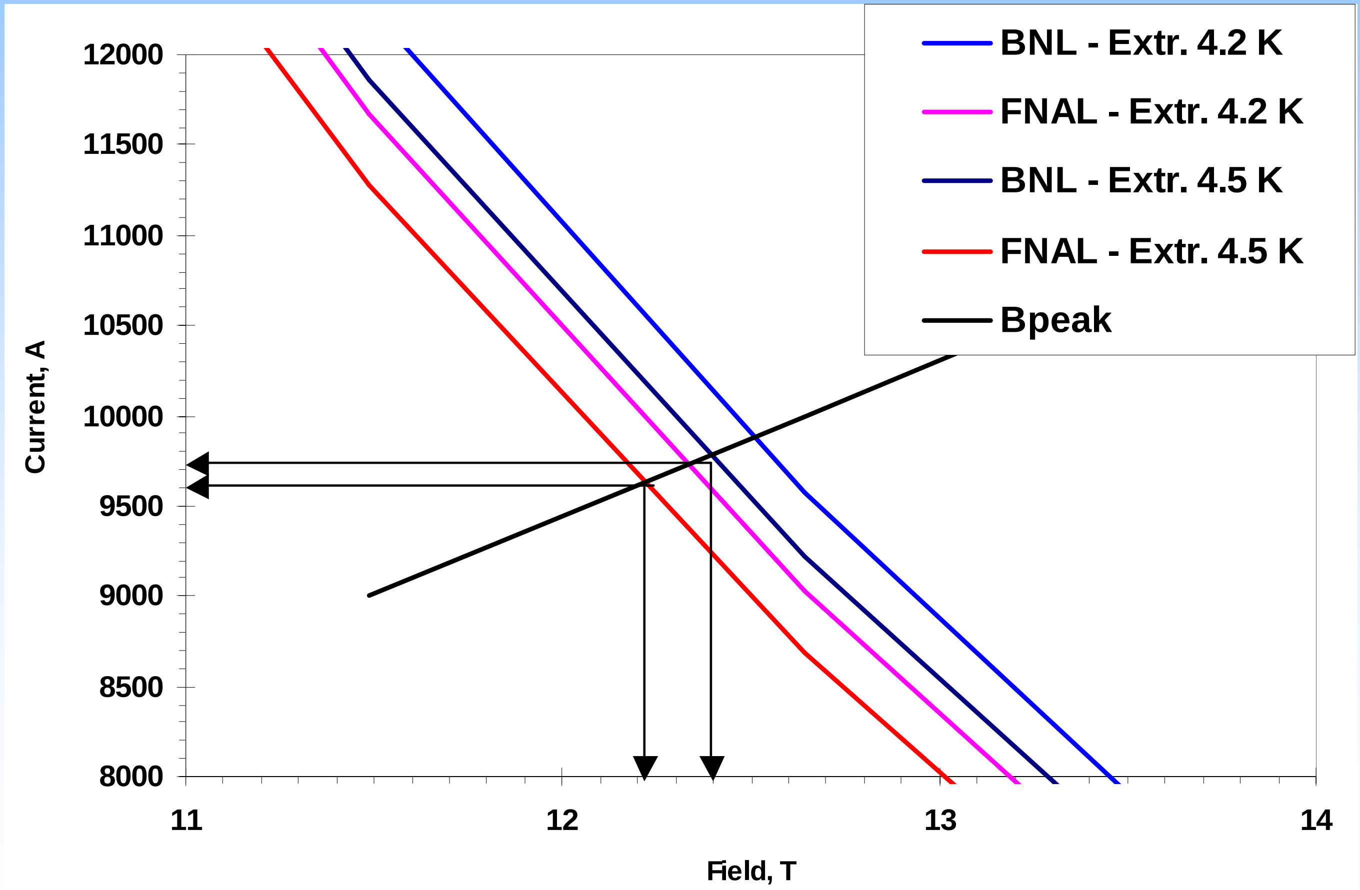


Additional Round Robin tests are planned. However…

SRS01-High Field Short Sample Limits

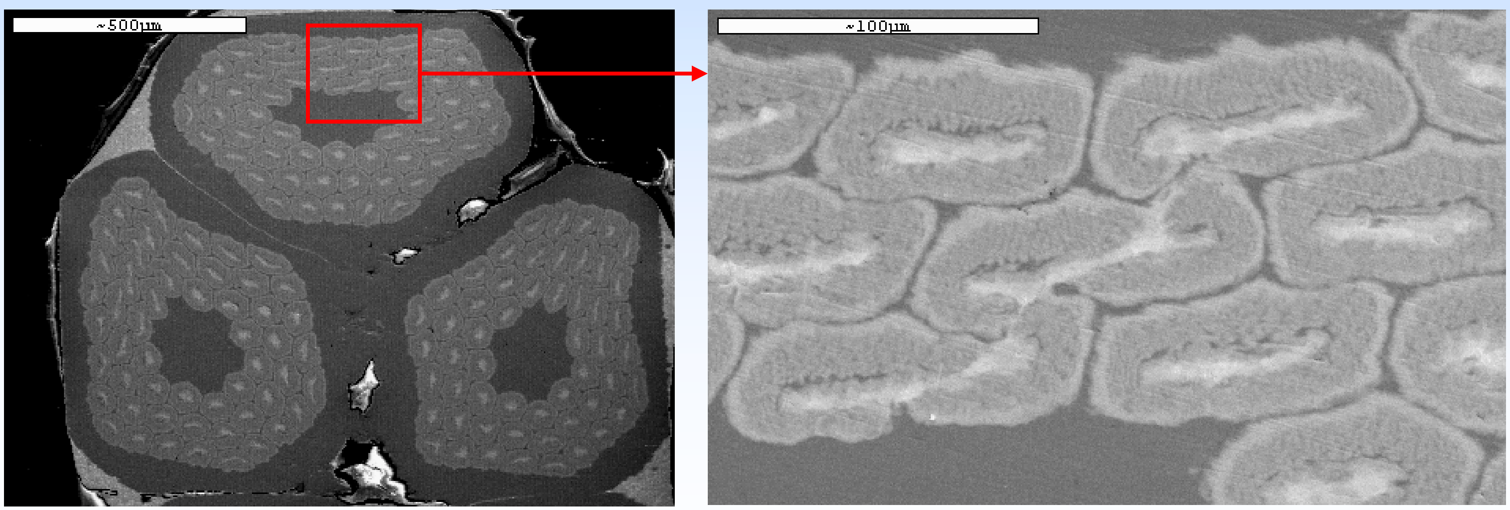
From Extracted strands
BNL: I_{ss} = 9780 A
FNAL: I_{ss} = 9630 A

Difference in I_{SS} prediction ~ 2%



Cable R&D

- Primary task is Cable Manufacture for LARP magnets
  - Optimize cabling parameters to minimize distortion of strand internal structure
    - ➢ reduce critical current degradation at the edges
    - ➢ reduce stability current degradation



Cabling Procedure

Present Nb_3Sn cabling procedure at LBNL

- Fabricate cable
  - Slightly over size
  - Anneal at 200C/2-4 hrs
    - Softens Cu and cable contracts by ~0.25% in length, thickness and width increases
    - May harden Sn core
- Re-roll to decrease thickness by 25-50 μm.
  - Compacts cable making it mechanically stable

Cabling Activity in FY06

All Nb_3Sn strands are RRP-54/61 from OST

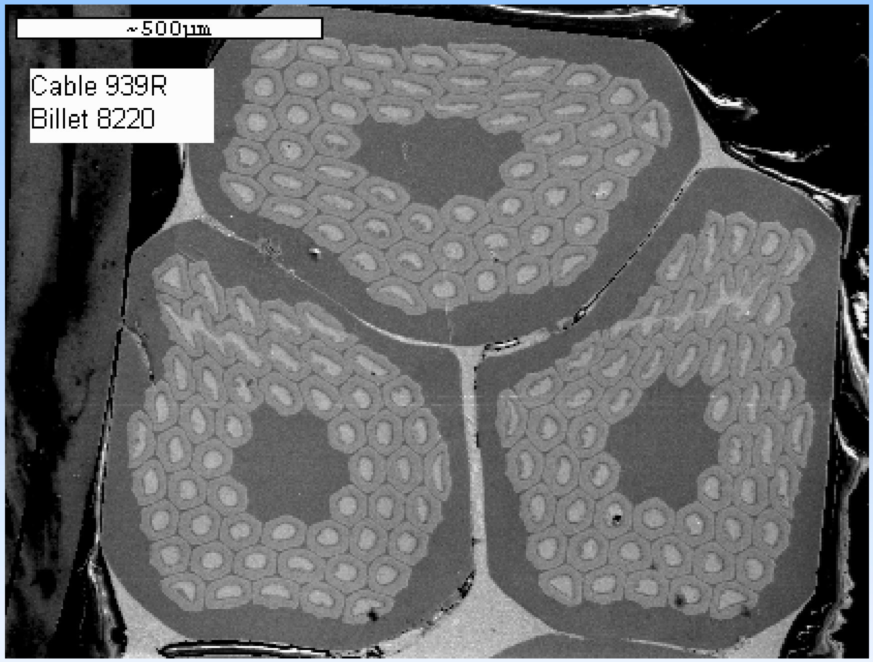
Cable TYPE	CABLE ID	STRAND	MAGNET	Cable Designation	Date / Manufacture
L7O	B0933	RRP	TQ	Prototype	10/5/2005
S3O	B0935	RRP	SRS01	Production	10/28/2005
L7O	B0936	RRP	TQ	Prototype	11/10/2005
L7O	B0939	RRP	TQC02	Production	3/9/2006
L7O	B0940	RRP	TQ	Production	3/20/2006
S3O	B0941	Cu	LR01	Practice	4/3/2006
S3O	B0942	RRP	LR01	Production	4/26/2006

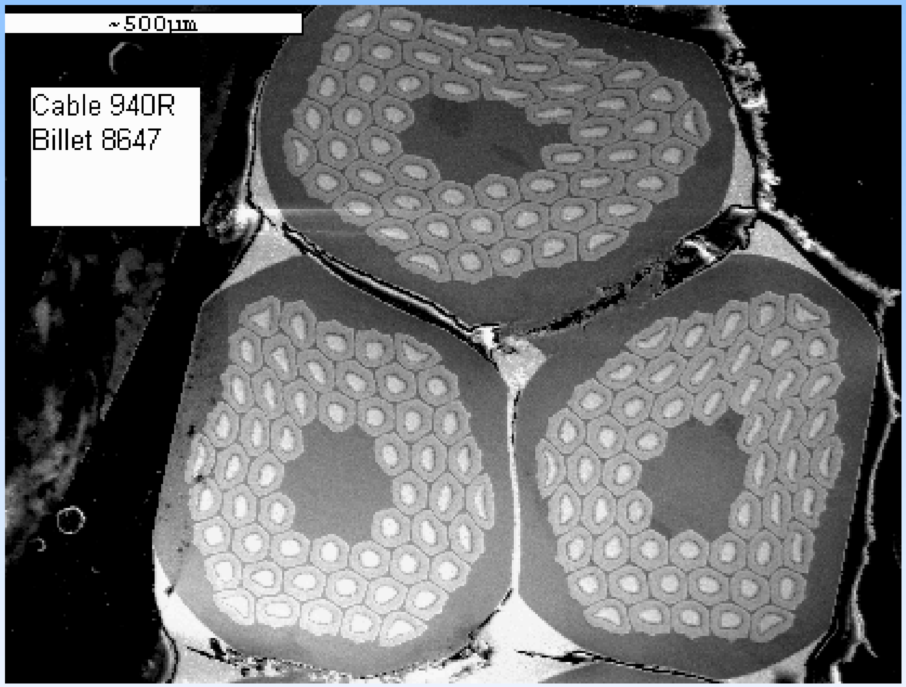
L7O -27 strand ,10mm wide, 1 deg keystone, 78mm pitch

S3O – 20 strand, 8mm wide, rectangular, 54mm pitch

Cabling Degradation
Minor Edge of 939R & 940R

Two cables are in specification of thickness, width, and keystone angle

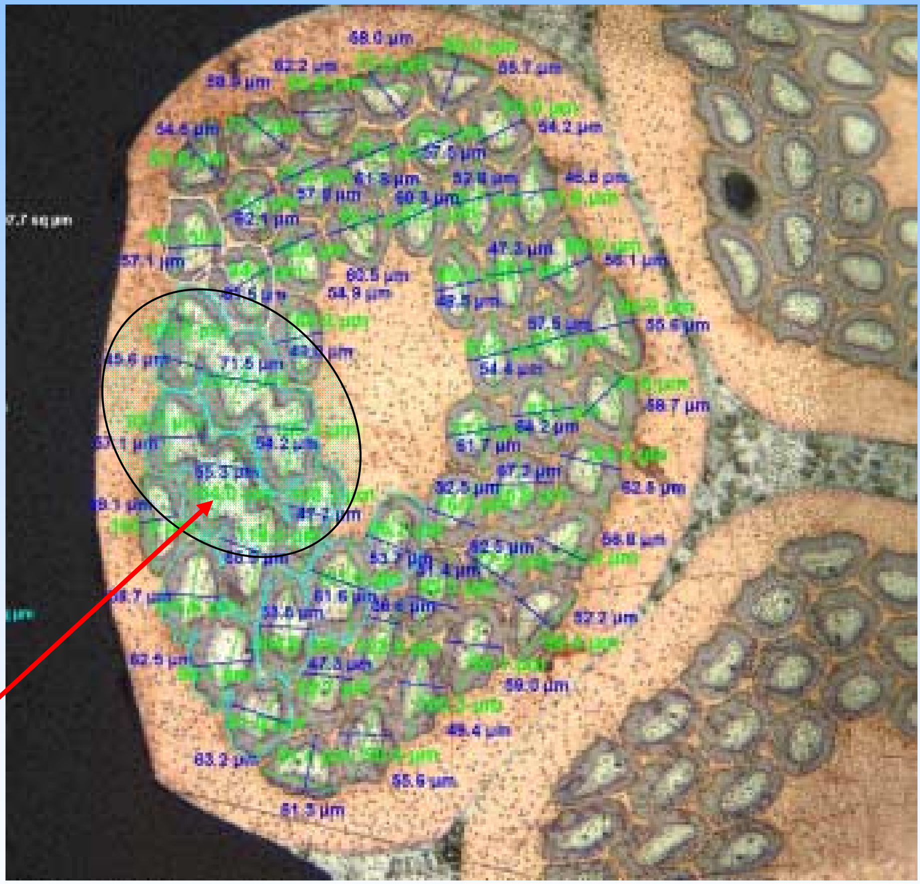




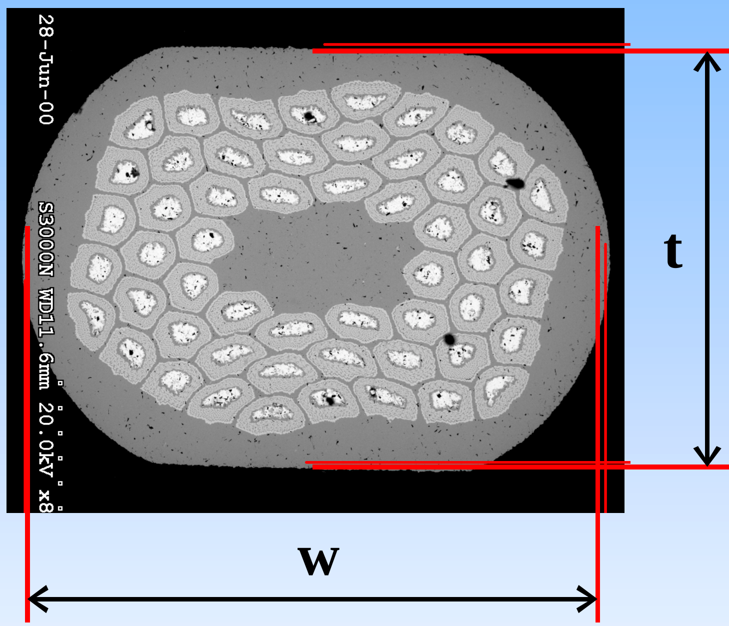
- Cable 939 over-compacted during the re-roll operation leading to significant barrier damage.
  - Cabling procedures being modified to avoid this problem.

Cabling Degradation.. Contd.

- Strand Deformation at the cable edges
  - Filament Distortion
  - Barrier Rupture
- Study this at the strand level
  - ➢ Simulate by rolling strands and examine
    - Effect on Ic
    - Effect of RRR changes on Is
    - Effect of Filament Merging (⇨local increase of magnetization) on Is



Roll Deformation



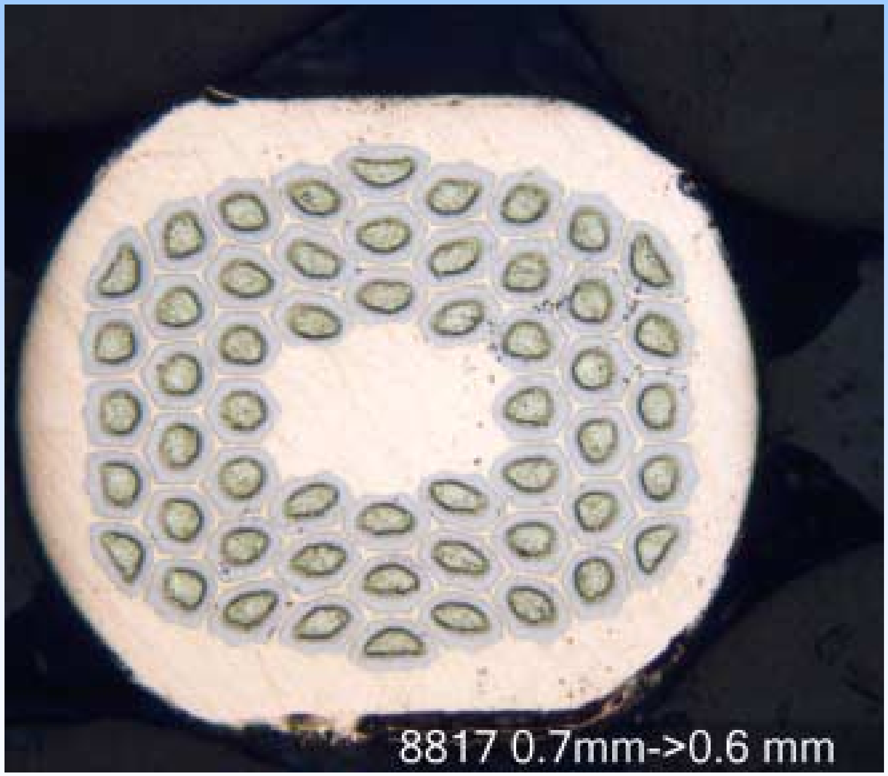
Roll strain=1-(t /d)

d=wire diameter

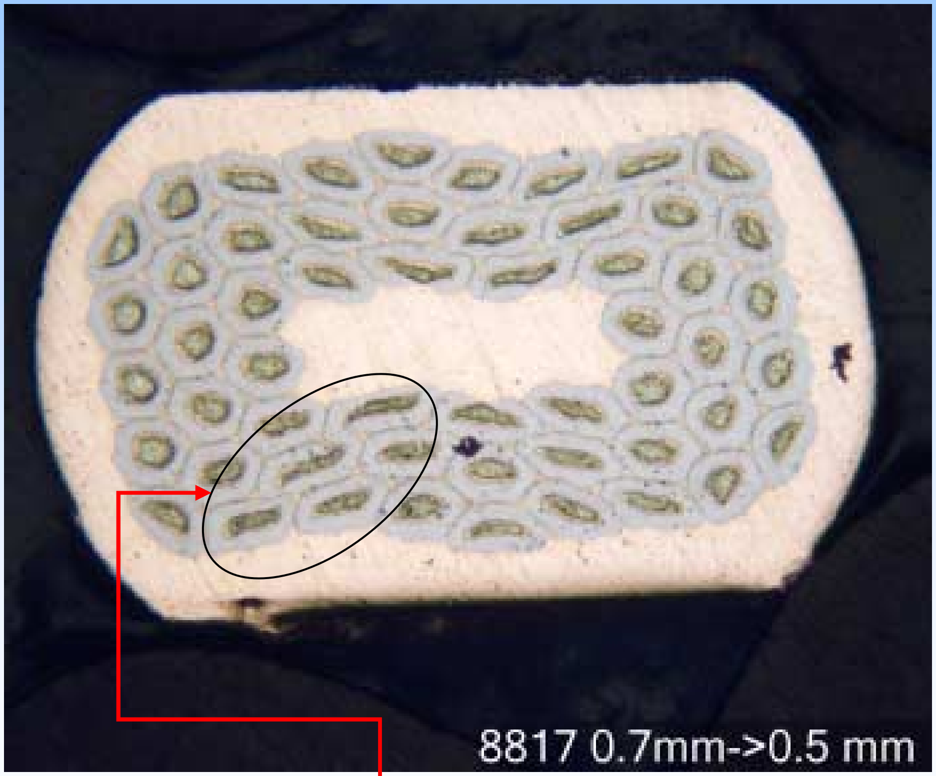
Rolled RRP-8817 Strands

For the TQ cable R_{strain} ~ 18%

R_{strain}=14%



R_{strain}=28%



Severe Filament Distortion

Preliminary results

Wire ID	HT_Temp °C	HT_Time hrs	Comments	Ic(12T) A	Is, A	RRR
RRP-8817-1A	651	48	0.7mm Round	572	1075	236
RRP-8817-1A-R	639	48	Rolled to 0.6mm	559	1200	138
RRP-8817-1A-R	639	47	Rolled to 0.5mm	518	975	68

H_A

I_s reduction at 28% roll deformation is minimal which is good.

Deformation tolerance may be improved by a modest increase in filament spacing (FNAL R&D billet 8853 is being evaluated)

Cable Testing

- FNAL
  – 28 kA SC transformer with fast (200kHz, 8-channel DAQ) for tests at self-field (1.8T)
    - Used to determine low field stability current
- No facility at the three labs to test cable samples at high fields 10-12 T.
- At present, cable is qualified based on transformer test and on extracted strand tests.

Cable Test at High Field
Transverse stress limits of TQ cable

Options being explored

- Test at the FRESCA facility at CERN, background field 10T, at 4.2 and 1.9K.
  - Cable samples pre-stressed at room temperature.
  - FNAL will modify existing tooling for sample holder which has been used previously at CERN to test MJR and PIT cable
  - This option is an opportunity for LARP-CERN collaboration in this activity. A test of a TQ cable is very likely to happen in the near future.
- Test at NHMFL in split-pair magnet, 11T, transverse stress applied at 4.2K
  - LBNL has experience in using this facility which has been dormant for 4 years and has yet to be re-commissioned. Cable sample holder tooling exists at LBNL
  - Discussions have been held with NHMFL who are keen to help
  - This option will take more time to develop

Summary

- Round and extracted strand testing procedures are well established to qualify strand and cable
- Test data on round strands from the three labs are quite consistent
  - That for extracted strands is within 10%. Further evaluation in progress
- Heat treatment optimization studies used to improve strand stability at the expense of Jc
- Minimize Cabling Degradation at minor edge for keystone cables
  - Optimization of cabling parameters and procedures
  - Rolled strand studies have been initiated for the new generation RRP conductor to study effect of roll deformation on Ic, RRR and Is.